



Music,



Math,



and

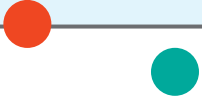


Mind

THE PHYSICS AND



NEUROSCIENCE OF MUSIC



David



Sulzer.

“Musicians shouldn’t be intimidated by the title *Music, Math, and Mind: The Physics and Neuroscience of Music*. This is a book that any musician or music fan will find both enjoyable and educational. The questions regarding the science, biology, and math related to music are made easily understandable, and the book is grounded in David’s passion for both creating and enjoying music. At the end, anyone reading this book will have a greater appreciation for the creative spirit and a way to understand music in even deeper ways.”

—Bob Neuwirth, singer-songwriter and record producer

“Putting the worlds of science and music together is an ambitious and potentially intimidating endeavor. But David Sulzer had me at paragraph one, where he writes ‘no one needs this book’! No, I don’t need it—but I find I do want it.”

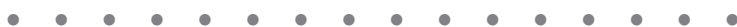
—John Schaefer, host of *New Sounds*, WNYC

“When your band protests, ‘Whaddaya mean “dynamics”? I’m playing as loud as I can!’—turn them onto the solid matter in *Music, Math, and Mind*. As to Soldier’s confection? A ribald reality check on what makes music matter and why we should mind. I’ve waited seventy-six years in a musical immersion to put a buzz on Dave Soldier’s flyleaf.”

—Van Dyke Parks, performer, arranger, producer, composer,
and lyricist, including with the Beach Boys

MUSIC, MATH, AND MIND

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The Physics and Neuroscience of Music

DAVID SULZER



COLUMBIA UNIVERSITY PRESS

New York

Columbia University Press
Publishers Since 1893
New York Chichester, West Sussex
cup.columbia.edu
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Library of Congress Cataloging-in-Publication Data

Names: Soldier, Dave, 1956– author.

Title: Music, math, and mind : the physics and neuroscience of music /
David Sulzer.

Description: New York : Columbia University Press, 2021. |

Includes bibliographical references and index.

Identifiers: LCCN 2020045865 (print) | LCCN 2020045866 (ebook) |
ISBN 9780231193788 (hardback) | ISBN 9780231193795 (trade paperback) |
ISBN 9780231550505 (ebook)

Subjects: LCSH: Music—Acoustics and physics. | Musical perception. |
Music—Physiological aspects. | Neurobiology. | Hearing.

Classification: LCC ML3805 .S62 2021 (print) | LCC ML3805 (ebook) |
DDC 781.1—dc23

LC record available at <https://lcn.loc.gov/2020045865>

LC ebook record available at <https://lcn.loc.gov/2020045866>



Columbia University Press books are printed on permanent and
durable acid-free paper.

Printed in the United States of America

Cover design: Noah Arlow

Contents

	<i>Nota Bene</i>	ix
	Introduction	1
	Introductory Listening	4
1	The Parameters of Sound	8
	Listening #1	30
2	The Math of Pitch, Scales, and Harmony	33
	Listening #2	58
3	Waves and Harmonics	63
	Listening #3	80
4	The Math of Sound and Resonance	83
	Listening #4	98
5	Math and Rhythmic Structure	102
	Listening #5	118
	Centerpiece: <i>The Sense of Hearing</i>	124

6	Brain Mechanisms of Rhythm	126
	Listening #6	145
7	Neural Mechanisms of Emotion	147
	Listening #7	158
8	Ear Physiology: How Air Waves Become Sound	159
	Listening #8	171
9	Deep Brain Physiology of Sound	172
	Listening #9	187
10	Sound Disorders, Illusions, and Hallucinations	189
	Listening #10	200
11	Animal Sound, Song, and Music	203
	Listening #11	249
	<i>Acknowledgments</i>	253
	<i>Appendix 1: Musical Pitch to Frequency Table</i>	257
	<i>Appendix 2: Further Reading</i>	259
	<i>Bibliography</i>	261
	<i>Author's Selected Compositions and Discography</i>	271
	<i>Index</i>	277

Nota Bene

This book is for musicians and art lovers who may have had little exposure to math, physics, and biology. It is written so that you can understand everything with no math beyond grade-school multiplication and division.

This is not a “pop science” book to be absorbed in a single reading: read a chapter that you are interested in, absorb what you can, and when you reread it, you will understand more. Honestly, I have been a professional scientist for three decades and still need to learn and relearn many of the basic concepts in these pages.

To some extent, math and science are foreign languages, and it is best to learn little by little: some topics required humanity centuries to comprehend, and particularly toward the end of the book, there remains far more to be discovered.

For ambitious readers, the “Math Boxes” use simple math to go a bit further and can be safely ignored by readers without losing the flow. Even these require only multiplication and division.

The “Sidebars” are tangential remarks.

MUSIC, MATH, AND MIND



Introduction

- Who needs a book on math's and the nervous system's roles in music?

Some of the questions that will introduce these chapters lack a clear answer, but this has one: *no one needs this book*.

The creation and appreciation of music do not require knowledge of the math and biology that allow it to exist. These topics are not taught to music students, and musicians create great work without knowing them. Still, understanding the basis of music, sound, and perception will explain some mysteries, open deeper ones, help you understand what you hear, and provide ideas for your own work.

The approach to contemporary musical education is rooted in a system developed to train orphans and abandoned children in Renaissance Naples. The word *conservatori* meant “places to save children,” and music provided a way for those who did not inherit a family trade to learn to compose, play instruments, and sing to make a living. The original conservatory, Santa Maria di Loreto, founded in Naples in 1537, was immensely successful, training the composers Alessandro Scarlatti and Domenico Cimarosa. The movement spread, with Antonio Vivaldi teaching at the Ospedale della Pietà for orphaned and abandoned girls in Venice and composing concerti like the *Four Seasons* for the school orchestra. The system migrated to the Paris Conservatory in 1784 and from there throughout the

world as conservatories broadened their mission to accept students from any family background.

Over these five hundred years, the purpose of musical training has always been to impart tools to make a living. For example, Johann Sebastian Bach, a god for composers, taught music theory classes at the Leipzig Thomas School so that students could perform on the organ during church services. Bach's lessons were bound in a book, *Precepts and Principles for Playing the Through Bass or Accompanying in Four Parts* (1738), modeled on the *Musical Guide* (1710) by Friedrich Erhard Niedt, a pupil of Bach's cousin Johann Nicolaus Bach. These books provide clear instructions in the techniques used by the Bach family, with rules for composing fugues and the popular dances like sarabandes and jigs: learning those rules can help you create a piece in that tradition.

In contrast, the creation of music in some other styles requires no theory classes—or even instrument or singing lessons—but simply talent, opportunity, and work. A pioneer of this approach was the French radio engineer Pierre Schaeffer, who in the 1940s composed exciting music by splicing together recording tape. Fifty years later, this approach was updated by the hip-hop group Public Enemy, who created instrumental tracks entirely by juxtaposing previously recorded sounds. Schaeffer and Public Enemy prove that with perseverance and access to the right tools, one can create brilliant music immediately without requiring years of training.

A thoughtful perspective on the issue of technical training versus instinct in creating music comes from the American composer and violinist Leroy Jenkins. Leroy grew up in the 1940s performing classical violin duos on the Chicago streets with his classmate, the future rock 'n' roll pioneer Bo Diddley, when lessons on instruments were typically part of the public school curriculum. Many of Leroy and Bo's classmates at Chicago's DuSable High School trained under the violinist and teacher Walter Dyett. Dyett's students included a high percentage of the top figures in jazz and pop, including the saxophonists Eddie Harris, Gene Ammons, and Clifford Jordan and the singers Dinah Washington, Johnny Hartman, and Nat King Cole.

Despite the success of Walter Dyett and others, starting in the 1970s, support for music lessons in many American public schools evaporated. Young people, like the Bronx DJs Kool Herc and Afrika Bambaataa, adapted the sparse instrumental resources available to them—drum machines and turntables from stereo supply stores—and used them to create a style that Bambaataa named hip-hop, presently the most popular musical style in the world.

Leroy's comment was that they, like his generation, developed a style from what was available because even in a desert of resources, "you can't kill human creativity."

An extreme example of creating music without training or theory would be music made by children the first time they are given musical instruments. In the 1960s, the electronic music pioneer Daphne Oram did just this by coaching British high school students to compose with kitchen and household appliances like vacuum cleaners—and they made a wonderful record.

Another approach is to ask children what music they like to listen to and then coach them on how to do something like it. With friends and collaborators, I have managed this with groups of children as young as three-year-olds, in Brooklyn (the Tangerine Awkestra), East Harlem (Da Hiphop Raskalz), and the Mayan highlands of Guatemala (Yok K'u). Each group made its own record in styles they loved, while playing instruments they handled for the first time. Their music is unconcerned with virtuosity and very aware of feelings and stories, and it can be as satisfying to listen to as work by professionals, who wouldn't be able to unlearn their craft to create the same way.

Whether music is made after years of training and knowledge or by children playing instruments for the first time, underlying all of this activity is an ancient and direct line of study initiated by natural philosophers in China, India, Egypt, and Greece. Their discoveries underpin the creation and comprehension of music but are unknown to almost all musicians.

Here are some basic questions on math, physics, and the nervous system that musicians care about but are not discussed in music theory classes:

- Which sounds are in and out of tune, and how are musical scales derived?
- Is it true that scales are really never in tune?
- What are overtones and harmonic sounds?
- Sound is formed from air waves that move in space and time. What shape are these sounds? How big, fast, and heavy are they? How are sound waves different in air, under water, or when traveling through the earth?
- Why do voices and instruments sound different from each other? Why do larger instruments play lower pitches?
- Given that we have only two eardrums and two ears, how are we able to identify many sounds that occur simultaneously?
- Is there a mathematical definition of noise and of consonance?
- How does the brain understand what it is listening to? (Warning: this does not yet have a satisfying answer.)
- How are emotions carried by music? (The same warning applies.)
- How do other animals hear and make sound differently from us?

If these issues are not taught to musicians and music lovers, it is not from a lack of curiosity. Artists and art lovers have of plenty of that, and this book is for them. You can't kill human creativity, and you might use this knowledge for new explorations.

Introductory Listening

Pierre Schaeffer's "*Etude aux casseroles, dite 'pathetique'*" was composed on recording tape in 1948. He created this music by assembling prerecorded sounds, including bits of a harmonica played by the blues musician Sonny Terry. It still sounds like music from the future.

Daphne Oram was also a pioneer of electronic music. For a project in 1968, likely inspired by John Cage, who used transistor radios as musical instruments, she coached English schoolchildren to create music using household appliances. Listen to "*Adwick High School Number 3*" by Linda Parker, a piece for metal sheet, tin lips, chimes, wire, frame, keyboards, wood block, echo sander, scraper, and whistle.

It's not hard to find "instrumentals" of vintage hip-hop tracks, that is, the musical portions without vocals. The first hip-hop hit, 1979's "Rapper's Delight" by the Sugar Hill Gang, was produced by the rock 'n' roll and disco singer Sylvia Robinson (her group Mickey and Sylvia had a major hit in the 1950s, Bo Diddley's song "Love Is Strange") and used a live band playing a theme from the disco group Chic, augmented by a DJ playing short phrases on a turntable.

Only three years later, "Planet Rock" by Afrika Bambaataa in 1982, rather than being performed by professional rock or R&B players and a live drummer, used only a drum computer (known as a drum machine, here the beloved Roland TR-808), with a vocoder, a turntable, and the keyboard player John Robie playing a theme from the German electronic rock group Kraftwerk on a synthesizer. The style, which they called "electronica," sounded more rigid than the Sugar Hill style on purpose, suggesting a robotic future.

About five years later, Public Enemy welded Schaeffer's approach to Bambaata's term "hip-hop" by assembling instrumentals from looped samples taken from other records. They were able to do this without recording tape thanks to the advent of faster computers that had just become available in studios. With the producers Hank Shocklee and Eric Sadler, their looped samples provided the ominous feel of their style: 1988's "Night of the Living Baseheads" uses tiny slices from at least twenty different songs during its three minutes, including bits of Aretha Franklin and David Bowie and many from James Brown's band.

The use of stripped-down and affordable electronic instruments led to very different styles in the Bronx, Chicago, and Detroit. The Chicago house and footwork styles and Detroit techno were mostly established by musicians who had little formal training, although some, including Larry Heard, the inventor of "deep house," were virtuoso performers of jazz and pop. The instruments central to these styles were—and continue to be—turntables, samplers, synthesizers, and drum machines. The "footwork" pioneer DJ Rashad took the genre's simultaneous syncopated rhythms to a futuristic level that points out new directions for others to explore.

Leroy Jenkins, as you might imagine from his broad experience in the classical, rock, and jazz traditions, created an extraordinary range of

compositions. One approach he used was to write very simple but unusual phrases as a basis for improvised longer compositions. A good start is his album *Space Minds, New Worlds, Survival of America*.

Bo Diddley stopped playing the classical violin after he heard the blues singer and guitarist John Lee Hooker; he went on to build his own trademark rectangular electric guitars and create his own style to become one of the pillars of rock 'n' roll. I played second guitar in his band, and he told me that although his daughter wanted to play the violin, he discouraged it because "there's no money in it." He nevertheless had a hit in 1959 playing a violin blues, "The Clock Strikes Twelve."

Da Hiphop Raskalz were four- to ten-year-old students I coached at the Amber Charter School in East Harlem, New York City. None played an instrument, but they immediately learned to operate synthesizers and drum machines and write their own lyrics and compositions; I only coached and mixed. Listen to "I Want Candy" by the Muffletons and "Do the Lollipop" by Sweetness.

The performers on *Yol K'u: Inside the Sun* were Mayan-speaking students from the Seeds of Knowledge school in San Mateo, Ixtatán, high in the mountains, the first high school in that part of Guatemala. A few knew how to play traditional pieces on the giant marimbas of the region, which had originally arrived from Africa, and we coached the kids to compose their own pieces. They composed the music by placing pieces of colored tape on the marimba's various slats. Listen to "Oracion de la Cruz."

The Tangerine Awkestra were three- to seven-year-olds from Brooklyn who created original pieces on instruments they didn't know how to play during a single afternoon-long rehearsal and recording session for a full CD. The flutist and composer Katie Down and I coached them to first write a story, for which they chose a space alien invasion, and then compose music for it. They came up with brilliant avant-garde "free improvisation" compositions. Try "Aliens Took My Mom."

A profound story involving the coaching of children to create their own music comes from Conakry, Guinea, where the Canadian jazz saxophonist Sylvain Leroux has been traveling for many years to teach ensembles in a school he founded in an abandoned aircraft hanger, L'École Fula Flute. The teachers include master musicians from the Fula tradition. The

students learn a chromatic version of the traditional flute, the *tambin*. Sylvain invented the chromatic *tambin* so that the instrument's repertoire could be expanded, and the students are taking off. Between their two CDs, you can hear them develop from beginners into professionals who have performed for Guinea's president: try "Bani."

1



The Parameters of Sound

How can we measure music? How fast, long, and tall is it?

When we hear a sound, *something* must move in the air and enter our ears. These are waves in the air, which is challenging to imagine. Fortunately, ocean waves provide help.

On the beach, we see waves where the air meets the water. When you wade in the ocean, you feel the power of the wave at its highest pressure—the *peak* or *crest* that pushes you toward the shore—and you may feel pulled away from the shore at its lowest point, known as the *trough*. The ocean waves also push and pull the air around them, creating air waves that we perceive as the sound of the ocean (figure 1.1).

SIDEBAR 1.1

There is a wide range of water waves. Ripple waves, seen when the wind blows over a puddle, are short wavelength (a few centimeters), with short amplitudes, and are rapid, usually several Hz.

On California surfing beaches, the waves in a swell have wavelengths of about 150 meters, are in the range of a meter in height, and are at a much slower frequency, around one wave every ten seconds (0.1 Hz).

A giant tsunami wave caused by an underwater earthquake can have a wavelength of over 100,000 meters and be tens of meters in amplitude, with a frequency of one wave per hour ($1 / 3600$ seconds = 0.0003 Hz, or 0.3 thousandths of a Hz).

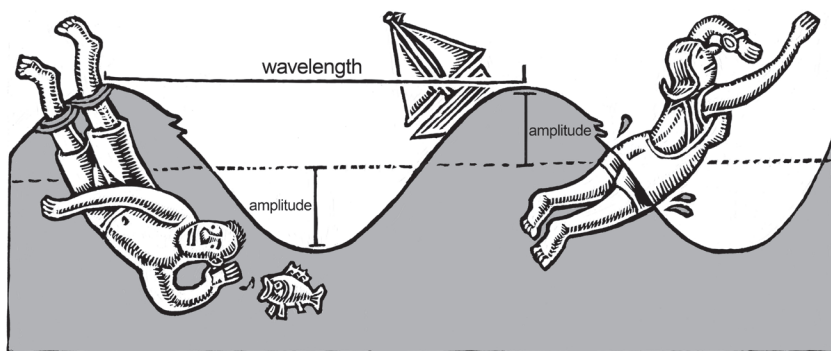


FIGURE 1.1 Waves at the beach

The waves you see and feel in the water are caused by wind, weather, and ocean currents. You also hear the sound driven by the push and pull of the water waves.

For a repeating or *periodic* wave, the *wavelength*, abbreviated as lambda (λ), is the distance between any two points where the cycle repeats. It can be measured between successive peaks or troughs.

The *amplitude* of the wave is the height measured from the midpoint of a wave to its peak or trough. We measure wavelength and amplitude in meters (*m*).

The number of waves that occur over time is the *frequency*, reported as waves per second (*s*) in units of hertz (Hz), after the physicist Heinrich Hertz (1857–1894). Two waves per second is a frequency of 2 Hz. The time it takes for a wave cycle to complete is known as the wave *period* and is the reciprocal of the frequency: the period of a 2 Hz wave is $1/2$ second.

At the beach, we watch *surface* waves, where individual water molecules remain relatively local, moving in circles, up and down, or back and forth. This can be pictured by the toy boat in the figure that bobs up and down or back and forth with the waves but is neither swept to the shore nor washed out to sea: these sideways movements are known as *transverse* waves. Likewise, in sound waves, individual air particles oscillate locally back and forth between higher-pressure local peaks and lower-pressure troughs, rather than moving long distances from one end of a room to the other.

Source: Art by Lisa Haney. Used with permission.

The tide is also a wave, and as high tide occurs at 12-hour-and-25-minute intervals, its frequency is $1/44,700$ seconds = 22 millionths of a Hz. If ocean waves repeated regularly (*periodically*) at a speed of at least twenty waves per second, the air waves they would produce would be heard as a musical tone. Periodic waves in air or water at 1 Hz are too slow to hear, but elephants begin to hear frequencies above 15 Hz. We begin to hear low vibrations at around 20 Hz. These very low frequencies are sometimes used in music: the low notes of a bass with a low B string “extension” is 30 Hz, and occasionally a church organ will play a very low C, at 16 Hz. That note is genuinely below our ability to hear: what we hear instead are higher multiples of the note, as explained shortly.

SIDEBAR 1.2

Musicians are familiar with these letter names for notes, but for nonmusicians: the convention is to name the notes of the scale from lower to higher pitches as A B C D E F G and then start all over again at the next higher A. The distance between the names of any of these notes and its next repeat is known as an *octave*. If this doesn’t yet make sense, stick with us; it will.

At the high end of our hearing, teenagers extend up to about 20,000 Hz, above which we humans do not perceive sound. This means that with good hearing, we can hear across a ten-octave range. Dogs hear as high as 45,000 Hz——thus the dog whistle they hear but we don’t——cats to about 80,000 Hz, mice to about 100,000 Hz, and some bats and whales to a ridiculous 200,000 Hz, more than three octaves higher than we can.

SIDEBAR 1.3

Abbreviations for Large and Small Numbers

Rather than writing out 200,000 Hz, we can substitute kilo (abbreviated *k*) for thousand and more easily write 200 kHz. The standard abbreviations for large

and small numbers are simple to remember because they are in powers of 1000 (10^3 , meaning 1 followed by three zeroes).

one thousand = $1000 = 10^3 = 1$ kilo (k)

one million = $1,000,000 = 10^3 \times 10^3 = 10^6 = 1$ mega (M)

one billion = $1,000,000,000 = 10^3 \times 10^3 \times 10^3 = 10^9 = 1$ giga (G)

one thousandth = $1/1000 = 1/10^3 = 10^{-3} = 0.001 = 1$ milli (m)

one millionth = $1/1,000,000 = 1/10^3 \times 1/10^3 = 10^{-6} = 0.000001$
 = 1 micro (μ , pronounced “mu”)

one billionth = $1/1,000,000,000 = 1/10^3 \times 1/10^3 \times 1/10^3 = 10^{-9}$
 = 0.000000001 = 1 nano (n)

The only common exception to the use of powers of three is “centi (c)” for one hundredth = 0.01, but that is generally used only for distance, measured in centimeters.

Beach Waves and Sound Waves

Water waves are helpful for understanding sound waves in the air, but there are important differences.

The peak of a water wave contains more molecules, and since liquids are hard to compress, the peak invades the airspace and becomes taller. This is known as a *transverse* wave, meaning that rather than along the long axis, in this case toward and away from the shore, the waves move in a perpendicular or sideways direction, in this case up and down. A transverse wave can also be seen in the sideways vibration of a plucked guitar string, where the string moves back and forth from where it was plucked, instead of back and forth between the ends.

Air is much more easily compressed than water. When a sound is projected from a singer or instrument, the air particles are alternatively compressed and relaxed, producing what is known as a *longitudinal wave*. For example, the movement of a stereo system speaker drives a sound wave by pushing and pulling the air in front of the speaker cone to produce regions of high (*compressed*) and low (*rarefied*) air pressure. A plucked guitar string, by vibrating sideways as a sideways transverse wave, also alternately pushes